



University of Technology Sydney

Faculty of Engineering and Information Technology

**Design and Control of a Novel Uninterrupted Dual
Input Powertrain System for Electric Vehicles**

A thesis submitted for degree of

Doctor of Philosophy

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2018

Certificate of Original Authorship

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

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- [2] **J. Liang**, H. Yang, J. Wu, N. Zhang, P.D. Walker, Power-on shifting in dual input clutchless power-shifting transmission for electric vehicles, Mech. Mach. Theory. 121 (2018) 487–501. (Chapter 2, 3, 4)
- [3] **J. Liang**, J.-H.J.-H. Zhong, Z.-X.Z.-X. Yang, Correlated EEMD and Effective Feature Extraction for Both Periodic and Irregular Faults Diagnosis in Rotating Machinery, Energies. 10 (2017) 1652. doi:10.3390/en10101652.
- [4] **J. Liang**, J. Wu, N. Zhang, Z. Luo, S. Zhu, Interval uncertain analysis of active hydraulically interconnected suspension system, Adv. Mech. Eng. 8 (2016). doi:10.1177/1687814016646331.
- [5] W. Yang, **J. Liang***, J. Yang, N. Zhang, Investigation of a novel coaxial power-split hybrid powertrain for mining trucks, Energies. 11 (2018). doi:10.3390/en11010172. (Chapter 2, 7)
- [6] J. Wu, **J. Liang**, J. Ruan, N. Zhang, P.D. Walker, Efficiency comparison of electric vehicles powertrains with dual motor and single motor input, Mech.

Mach. Theory. 128 (2018) 569–585.

doi:<https://doi.org/10.1016/j.mechmachtheory.2018.07.003>. (Chapter 5)

- [7] J. Wu, **J. Liang**, J. Ruan, N. Zhang, P.D. Walker, A robust energy management strategy for EVs with dual input power-split transmission, Mech. Syst. Signal Process. 111 (2018) 442–455. doi:[10.1016/j.ymssp.2018.04.007](https://doi.org/10.1016/j.ymssp.2018.04.007). (Chapter 5)
- [8] H. Yang, Y. Zhang, **J. Liang**, J. Gao, P.D. Walker, N. Zhang, Sliding-Mode Observer Based Voltage-Sensorless Model Predictive Power Control of PWM Rectifier Under Unbalanced Grid Conditions, IEEE Trans. Ind. Electron. 65 (2018) 5550–5560. doi:[10.1109/TIE.2017.2774730](https://doi.org/10.1109/TIE.2017.2774730).
- [9] H. Yang, Y. Zhang, **J. Liang**, J. Liu, N. Zhang, P. Walker, Robust Deadbeat Predictive Power Control with a Discrete-time Disturbance Observer for PWM Rectifiers under Unbalanced Grid Conditions, IEEE Trans. Power Electron. (2018). doi:[10.1109/TPEL.2018.2816742](https://doi.org/10.1109/TPEL.2018.2816742).
- [10] H. Yang, Y. Zhang, **J. Liang**, B. Xia, P.D. Walker, N. Zhang, Deadbeat control based on a multipurpose disturbance observer for permanent magnet synchronous motors, IET Electr. Power Appl. 12 (2018) 708–716.
- [11] H. Yang, Y. Zhang, P.D. Walker, **J. Liang**, N. Zhang, B. Xia, Speed sensorless model predictive current control with ability to start a free running induction motor, IET Electr. Power Appl. 11 (2017). doi:[10.1049/iet-epa.2016.0481](https://doi.org/10.1049/iet-epa.2016.0481).

- [12] J.-H. Zhong, **J. Liang**, Z.-X. Yang, P.K. Wong, X.-B. Wang, An Effective Fault Feature Extraction Method for Gas Turbine Generator System Diagnosis, *Shock Vib.* 2016 (2016). doi:10.1155/2016/9359426.

International conferences

- [1] H. Yang, Y. Zhang, **J. Liang**, N. Zhang, W. Paul, A robust deadbeat predictive power control with sliding mode disturbance observer for PWM rectifiers, in: *Energy Convers. Congr. Expo. (ECCE)*, 2017 IEEE, 2017: pp. 4595–4600.
- [2] **J. Liang**, H. Yang, W. Mo, N. Zhang, and P. D. Walker, Modelling and Control of Dual Input Clutchless Transmission for Electric Vehicles, in: *Intern. Conf. on Adv. Veh. Powert. (ICAVP)*, 2017 (best paper award)

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Abbreviations

HEV	-	Hybrid Electric Vehicle
PHEV	-	Plug-in Hybrids Electric Vehicles
EV	-	Electric Vehicle
FCV	-	Fuel Cell Vehicles
CVT	-	Continuously Variable Transmission
DCT	-	Dual Clutch Transmission
EMS	-	Energy Management Strategies
ICE	-	Internal Combustion Engine
AMT	-	Automated Manual Transmission
DP	-	Dynamic Programming
SA	-	Simulated Annealing
GA	-	Genetic Algorithms
PMP	-	Pontryagin's Minimum Principle
PSC	-	Power Sharing Control
THS	-	Toyota Hybrid System
ECVT	-	Electronic Continuously Variable Transmission
CHS	-	China Hybrid System
IVT	-	Infinitely Variable Transmission
FHS	-	Ford Hybrid System
UMST	-	Uninterrupted Multi-Speed Transmission
RTCS	-	Real-Time Control Strategy
SOC	-	State of Charge
FOC	-	Field Oriented Control

DTC - Direct Torque Control

MPTC - Model Predictive Torque Control

MPFC - Model Predictive Flux Control

MT - Manual Transmission

AT - Automatic Transmission

CLAMT - Clutchless Automated Manual Transmission

LA-92 - Los Angeles 92 / Unified Cycle Driving Schedule

HWFET- Highway Fuel Economic Test

Abstract

The automotive powertrain is one of the most important subsystems of any vehicle whose major function is to convert the stored energy to kinetic energy and deliver it as tractive load to the road. In order to reduce the harmful emissions and the dependence on fossil fuels, the development of new technology will improve the overall efficiency, the drivability and the driving comfort, and reduce the tailpipe emissions. However, the inclusion of electric machines alone does not guarantee these improvements, proper transmission structure design and adequate control strategy should be designed to fully exploit the potential of the whole system, thereby maximizing the benefits to end users.

In order to achieve the aforesaid benefits of electric vehicle, a novel dual input clutchless transmission configuration is proposed which consists of an automated manual transmission (AMT) and a fixed gear pair. It has the merits of low manufacturing cost, robustness and easy implementation. With the proposed gear shift control strategy, the novel configuration could eliminate the torque interruption of conventional AMT systems, improving the drivability and driving comfort.

To fully exploit the efficiency improvements of the proposed system, a real time power sharing control strategy is proposed to balance the load distribution between the two motors. By adequately choosing the gear position and distributing the power demand, the overall efficiency could be improved by more than 10%.

The proposed power sharing strategy has the disadvantage encountered by many other energy-oriented energy management strategies which is high gear shifting frequency. To keep a high overall efficiency and at the same time significantly reduce the shift frequency, a shifting stabilizer is proposed and embedded in to the control strategy.

At last, a modified hybrid configuration based on the proposed concept is developed for mining trucks. The hybrid system could satisfy the specific requirements of mining trucks and present high overall efficiency and drivability.

To evaluate the effectiveness of the proposed approaches, various detail mathematical models have been built and tested in sets of driving conditions which could reflect the practical implementations.